

Variation of phosphorus leached from Pennsylvanian soils amended with manures, composts or inorganic fertilizer

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Abstract

The continued application of P as fertilizer or manure at rates exceeding crop requirements can increase soil P concentrations and the potential for P loss to surface waters. Limits for eutrophication of flowing waters not discharging directly into water bodies of 0.01 mg dissolved reactive P (DRP) and 0.1 mg total P (TP) l⁻¹, can be readily exceeded in areas with P enriched soils. Little information is available on how long P discharge will remain above environmental thresholds, particularly for subsurface flow. Thus, this work looked at the effect of applying P (as mineral fertilizer, dairy manure and compost, and poultry manure and compost at 0–200 kg P ha⁻¹ per year for 5 years), to a Hagerstown silt loam on P leached from lysimeters (30 cm deep) with rainfall generating high flow (330 cm per 5 months; high-flow lysimeters) and low flow conditions (165 cm per 5 months; low-flow lysimeters). For high-flow lysimeters, most P was leached from dairy compost (88 mg DRP and 148 mg TP) and poultry manure (41 mg DRP and 83 mg TP) amended soils compared with mineral superphosphate (26 mg DRP and 43 mg TP) and dairy manure (26 mg DRP and 59 mg TP). Similar trends but lower losses were observed for the low-flow lysimeters. Among the 50 lysimeters, Mehlich-3 soil P thresholds of 100 and 130 mg kg⁻¹ occurred for DRP and TP, respectively. Above these thresholds, DRP and TP loss was enhanced. The decrease of P concentrations leached (inorganic and organic P forms, y) with time (t , days) could be described by a power function ($y = \alpha t^\beta$). The rate of decrease in P leached (β) was quicker at high than low flow rates. Using this equation, it was estimated that for a soil of 100 mg kg⁻¹ Mehlich-3 P under high-flow conditions would take about 3 years for DRP to fall below 0.01 mg L⁻¹ and 6 years under low flow conditions. Clearly, once soil P concentrations become elevated via management, it can take several years for P enriched drainage waters to decline below “acceptable” levels.

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1. Introduction

Areas with intensive livestock farming often have soils enriched with phosphorus (P) due to the addi-

tion or disposal of manure (Withers et al., 2001). The soil test P (STP) concentration of these soils can be as much as twice or three times the concentration required for optimum plant growth (Sharpley et al., 1998). This increases the potential for P loss to surface water and therefore eutrophication (Kellogg and Lander, 1999).

In areas of Europe and North America, P-rich soils are common (Fixen, 1998; Skinner and Todd,

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1998). Until about 15 years ago, there was a common misconception within the literature that P loss via subsurface pathways was negligible as P is strongly sorbed to soil and thus, only surface pathways were of concern (Sharpley and Menzel, 1987). However, in free-draining soils and those where drainage is enhanced (e.g., tile drainage), P can be lost in environmentally significant quantities (Heckrath et al., 1995; Hesketh and Brookes, 2000).

For management purposes, the use of STP limits to minimize P loss provides the farmer with a tool they are familiar with for agronomic purposes and could adopt with a minimal increase in cost or possible resistance. Work has quantified the pool of P that could be potentially lost from different soils with specific environmental tests such as Fe-oxide strips and Fe-oxide gels that serve as near-infinite sinks for P (e.g., Lookman et al., 1995; Koopmans et al., 2001). However, fewer studies have quantified this pool in terms of agronomic STP measurements or actual P losses. Thus, the first objective was to quantify P losses in subsurface drainage from soils with a range of STP concentrations, ranging from deficient (<50 mg Mehlich-3 P kg⁻¹) to excessively enriched (e.g., >250 mg Mehlich-3 P kg⁻¹) (Beegle, 1999).

Previous work has shown that the potential pool of P available for loss, as measured by successive extractions with Fe-oxide strips, can be approximated with a Mehlich-3 extraction (McDowell and Sharpley, 2002). However, little information is available on the decline in subsurface drainage P with continued leaching, as a function of STP. Thus, the second objective was to investigate the relationship between subsurface drainage P and STP for intact soil columns of a Hagerstown silt loam soil. Finally, the third objective was to test the effect of increased drainage, designed to mimic either supplementary irrigation or a series of 'wet years', on the rate of P loss and soil P depletion.

2. Materials and methods

2.1. Soils and treatments

The soil is a fine, mixed, mesic Hagerstown silt loam (Luvisol or Typic Hapludalf) under perennial ryegrass (*Lolium perenne* L.) and located at a site on the Rock Springs farm near State College, Pennsyl-

Table 1

Water extractable P (mg kg⁻¹), TP (mg kg⁻¹), total N (g kg⁻¹) organic C (g kg⁻¹) and percent dry matter of the amendments used

P amendment	Water extractable P	TP	Total N	Organic C	Dry matter
Dairy manure	2030	3900	17.0	346	32.6
Dairy compost	2410	16530	25.7	323	37.0
Poultry manure	7430	28650	57.0	367	38.5
Poultry compost	2030	9440	14.4	123	68.0
Superphosphate	160000	200000	0	0	100

vania, USA. The unamended soil has a clay content of 190 g kg⁻¹, organic C concentration of 21.7 g kg⁻¹ and pH of 6.5. Inorganic fertilizer (triple superphosphate, referred to here as 'superphosphate'), poultry and dairy manure (C to P ratio 13 and 89, respectively) and poultry and dairy compost (C to P ratio 13 and 20, respectively) were applied in the spring of each year for 5 years (1995–1999) at rates of 0, 25, 50, 100 and 200 kg P ha⁻¹ to duplicate 2 m diameter plots (Table 1; Sharpley and Moyer, 2000). Typical P amendment rates in the area can typically be as high as 100 kg P ha⁻¹. Soil samples (the bulk of three, 2.5 cm diameter cores) were then taken within the rings to a 5 cm depth, air-dried, sieved (<2 mm) and stored until analyzed.

Lysimeters (50) were collected in June 2000 (when soil moisture was 5–10% greater than permanent wilting point) and taken to a greenhouse facility at University Park, Pennsylvania, USA (Fig. 1). Lysimeters were taken by driving a 30 cm length of 19 cm diameter PVC pipe into dry soil with one-stroke of a 2 t drop-hammer. The inside of the pipe was coated with paraffin wax to seal between the soil and lysimeter (Fig. 1). More wax was placed at the bottom than the top to give a more even distribution when driving it into the soil. Additional edge flow restriction is gained by the swelling action of dry soil when wetted. Acid-washed sand was used to fill any void space (less than 1 cm) between the soil and base cap (Fig. 1). A 1 cm diameter hole was drilled in the base cap, a small 5 cm tube glued in its place and glass wool inserted to prevent any loss of sand (Fig. 1; McDowell and Sharpley, 2001).

To half the lysimeters (one replicate of each treatment denoted as 'high flow'), rainfall (tap water, P concentration less than detection limit of

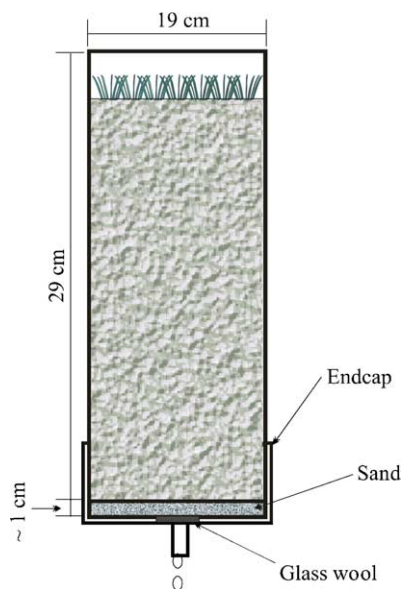


Fig. 1. The design and construction of the lysimeters (adapted from McDowell and Sharpley (2001)).

0.005 mg l⁻¹) was applied every 6 h for 10 min using a commercial drip-irrigation system (Rainbird¹), calibrated to deliver 0.945 l h⁻¹ (total rainfall 2.2 cm per day). The remaining lysimeters ('low flow') received half the rainfall (5 min every 6 h). This continued for a period of 5 months in an environmentally controlled greenhouse (temperature >10 °C). During irrigation, pasture was cut and returned to the top of the lysimeters approximately every 3–4 weeks. Every 30 days, starting from 3 days after the onset of artificial rainfall, bulked samples of 24 h drainage were collected. In general, some difference was noted in drainage volume from the beginning of irrigation compared to the end due to decreased water loss via evapotranspiration (a maximum of 150 ml difference). However, the infiltration capacities of the lysimeter soils were never exceeded (i.e., no ponding), meaning any change in redox conditions was unlikely. For the high-flow lysimeters, a mean drainage volume was calculated to be 0.475 l, while a mean drainage volume was calculated as 0.241 per day (defined as 24 h). Each drainage sample was split into two, with one-half filtered through

a 0.45 µm cellulose-nitrate syringe filter. Both filtered and unfiltered samples were stored at 4 °C until analysis.

Loads for P loss of each fraction were estimated as the sum total of P concentration at each sampling (assumed to approximate P concentrations for 30 days) multiplied by the mean drainage volume and extrapolated until the next sampling time (i.e., for 30 days). Data referred to here as loads refer to the sum total for each group of amended lysimeters (e.g., sum of P from lysimeters receiving 0, 25, 50, 100, and 200 kg P ha⁻¹ of dairy manure).

2.2. Soil and water analyses

All soil analyses were done in duplicate. Air-dried soils were analyzed for total P (TP) following a Kjeldhal digestion (Taylor, 2000), Mehlich-3 extractable P (Mehlich, 1984) and CaCl₂-P on a centrifuged (3 min at 3000 rpm) and filtered (Whatman #42) extract of soil (soil:solution ratio of 1:5) shaken in 0.01 M CaCl₂ for 30 min. The method of Watanabe and Olsen (1965) was used for all P determinations.

For drainage waters, both filtered and unfiltered samples were digested (Taylor, 2000) and TP (in unfiltered sample) and total dissolved P (TDP in filtered sample) determined after neutralization with 10 M NaOH. Particulate P (PP) was calculated as the difference between TP and TDP, while dissolved organic P (DOP) was calculated as the difference between TDP and dissolved reactive P (DRP, largely orthophosphate, measured in an undigested, filtered sample).

2.3. Statistical analyses and interpretations

Summary statistical data (means and standard errors) and the parameters of line fits (constants, correlation coefficients and levels of significance) were obtained using SPSS v10.0 (SPSS, 1999). Data were log transformed before fitting via linear regression to a power function:

$$y = \alpha t^{\beta} \quad (1)$$

where y is the concentration of a P fraction in drainage after each sampling (mg P l⁻¹), t the drainage sample number (numbered 1–5, each representing 24 h drainage and sampled at 30-day intervals) and α and

¹ Mention of trade names does not imply endorsement by the USDA.

β are the constants relating to the initial concentration of P in drainage and the change in concentration with time, respectively. Standard errors for the fit of the power equation to data ranged from 0.003 to 0.078 with a median and mean of 0.015 and 0.020. For the calculation of correlation coefficients between Mehlich-3 extractable P or TP and β , the inverse square of the standard error of β was used to weigh each data point.

It is not possible to quantify concentrations and loads of P measured in this leaching study as being related to field values. The rainfall rates applied are approximately three times and 50% greater than annual rainfall for the area (high- and low-flow lysimeters, respectively). However, the experimental technique of using intact soil cores and continued rainfall applications to the surface, does allow an evaluation of the relative effects of previous P applications as fertilizer or manure on subsurface drainage P, effect of flow volume, and the relationship between STP and subsurface drainage P. Further, the application of more than annual rainfalls over 5 months, allows an experimental assessment of relative changes in subsurface drainage P with amount of water applied, over a shorter period than with field observations. Thus, it enables relative comparison of treatment effects in support of general recommendations regarding P management within a “reasonable” time frame.

3. Results and discussion

3.1. P leached in relation to soil P and amendment type

Mean estimated loads for the loss of each P fraction under each flow rate and amendment type are given in Table 2. A comparison of P loads given in Table 2

Table 2

Estimated total load (mg) and standard error in parentheses of each P fraction lost

P fraction ^a	Dairy manure	Dairy compost	Poultry manure	Poultry compost	Superphosphate
Low-flow lysimeters					
DRP	12 (1)	37 (2)	19 (1)	9 (1)	10 (1)
DOP	5 (1)	9 (1)	3 (1)	4 (1)	3 (1)
TDP	17 (1)	36 (2)	21 (1)	13 (1)	13 (1)
PP	5 (1)	8 (1)	6 (1)	7 (1)	8 (1)
TP	22 (1)	42 (2)	27 (1)	20 (1)	21 (1)
High-flow lysimeters					
DRP	15 (1)	50 (3)	25 (1)	17 (1)	15 (1)
DOP	13 (1)	15 (1)	16 (1)	15 (1)	7 (1)
TDP	27 (1)	62 (3)	42 (1)	31 (2)	22 (1)
PP	6 (1)	14 (2)	7 (1)	3 (1)	3 (1)
TP	33 (1)	76 (6)	49 (2)	34 (2)	25 (2)

^a DRP, dissolved reactive P; DOP, dissolved organic P; TDP, total dissolved P; PP, particulate P; TP, total P.

and the inorganic or organic P soluble in water of each amendment (Table 3), would suggest that the greatest quantity of DRP loss (mainly orthophosphate) should occur from the superphosphate amended soils (greatest water solubility and 100% inorganic P). This was not the case, as most DRP was leached from the dairy compost amended soils followed by poultry manured soils. However, Sharpley and Moyer (2000) showed that among the organic amendments, dairy compost contained the greatest proportion of inorganic P; this agrees with the relative load data among the manures and composts. It is likely that orthophosphate applied in the superphosphate was strongly sorbed to the soil, whereas small amounts of organic matter applied in the compost facilitated P loss by blocking P sorption sites (Bhatti et al., 1998; Borggaard et al., 1990).

Among soils, Mehlich-3 extractable P concentrations varied from 12 to 270 mg kg⁻¹, while DRP and TP ranged from 0.01 to 0.75 mg l⁻¹ and

Table 3

Proportion (%) of inorganic and organic P soluble in water as a fraction of TP and the total proportion of P forms in each amendment

Fraction	Form	Dairy manure	Dairy compost	Poultry manure	Poultry compost	Superphosphate
Water	Inorganic	51	15	26	21	100
	Organic	12	1	8	1	–
Total	Inorganic	63	92	84	87	100
	Organic	25 ^a	5	14	11	–

^a The difference between the sum of inorganic and organic P forms represents residual P as determined by sequential extraction. Data from Sharpley and Moyer (2000).

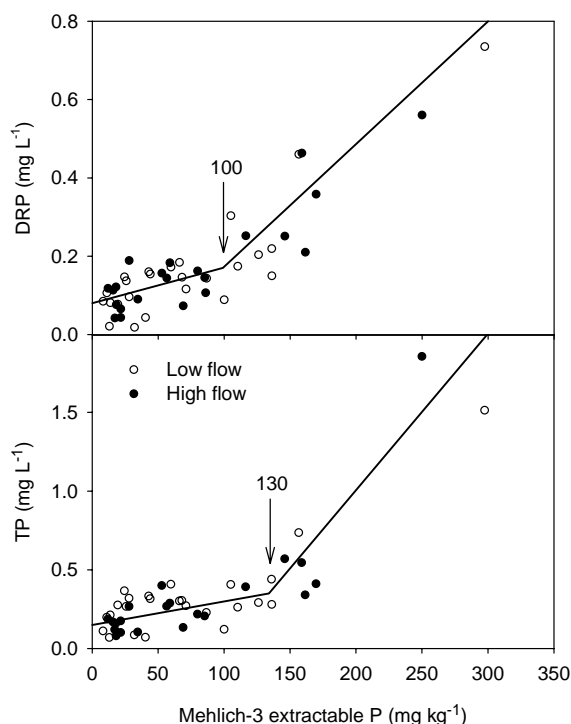


Fig. 2. The relationship between Mehlich-3 extractable P and DRP and TP in drainage after the first sample of drainage.

0.05–1.8 mg l⁻¹, respectively (Fig. 2). Previous work has shown CaCl₂-P can be a good indicator for P loss in subsurface drainage when plotted against STP (Hesketh and Brookes, 2000). Additional work has shown CaCl₂-P can also estimate the concentration of P loss in drainage waters (McDowell and Sharpley, 2001). When plotted against STP (Mehlich-3 extractable P) a threshold of 100 for DRP and 130 mg kg⁻¹ for TP is evident, with the potential for enhanced P leaching above these STP concentrations. However, no such relationship is evident for the other P fractions (OP, TDP or PP) and probably only relates to TP due to the large proportion of DRP present (50–72% TP).

In general, the standard error of the split-line model used to generate the threshold in Mehlich-3 extractable P concentration was 10% or less. Hence, the estimates are reasonably precise and can be attributed to the simple nature of the model where all data points contribute towards the generation of the two slopes that meet at the STP threshold. More variance was accounted for

by fitting the split-line model than by a simple linear regression, and no significant advantage was gained by plotting other non-linear functions (e.g., *F*-test of variance accounted for by exponential or power function not significantly better than the split-line model).

3.2. Variation of P leached with time and soil P concentration

To compare trends in P concentration leached with time, data were fitted to a power function ($y = \alpha t^\beta$; see Section 2.3). By comparing β values, the relative exhaustion or enrichment of a P fraction can be determined; the greater the magnitude of β , the faster STP is being exhausted or enriched.

An example of P leached for each drainage sampling is shown in Figs. 3 and 4 for soils receiving the greatest rate of amendment and an unamended soil for both flow rates. In all but two occasions (PP loss in two high-flow lysimeters), β values were negative indicating a net loss of P with time. By far the greatest loads of P for all five rates of P applied were accounted for by dissolved fractions (Table 2), as were the greatest initial losses (Figs. 3 and 4). With time, the difference between PP and dissolved fractions decreased, presumably as particulates were flushed out of the lysimeters. In manure and compost amended soils, much more P was leached in organic fractions compared to unamended and superphosphate amended soils. This is well established in other studies and attributed to both the larger proportion of organic P applied (Table 3), and greater mobility of organic P forms compared to orthophosphate (Chardon et al., 1997; Frossard et al., 1989).

Collectively, β values for DRP loss were not significantly correlated to CaCl₂-P, Mehlich-3 extractable P or TP. Previous work has shown that CaCl₂-P can approximate the concentration of P loss in subsurface drainage waters (McDowell and Sharpley, 2001). However, it cannot estimate the overall pool of P available for loss, whereas some evidence suggests a Mehlich-3 extraction can (McDowell and Sharpley, 2002). A more in-depth analysis of the data reveals that when these parameters were plotted for each amendment significant correlation coefficients were obtained (Table 4). The exact reason for this discrepancy is unclear, but probably relates to the different quantities and types of organic and inorganic materials applied

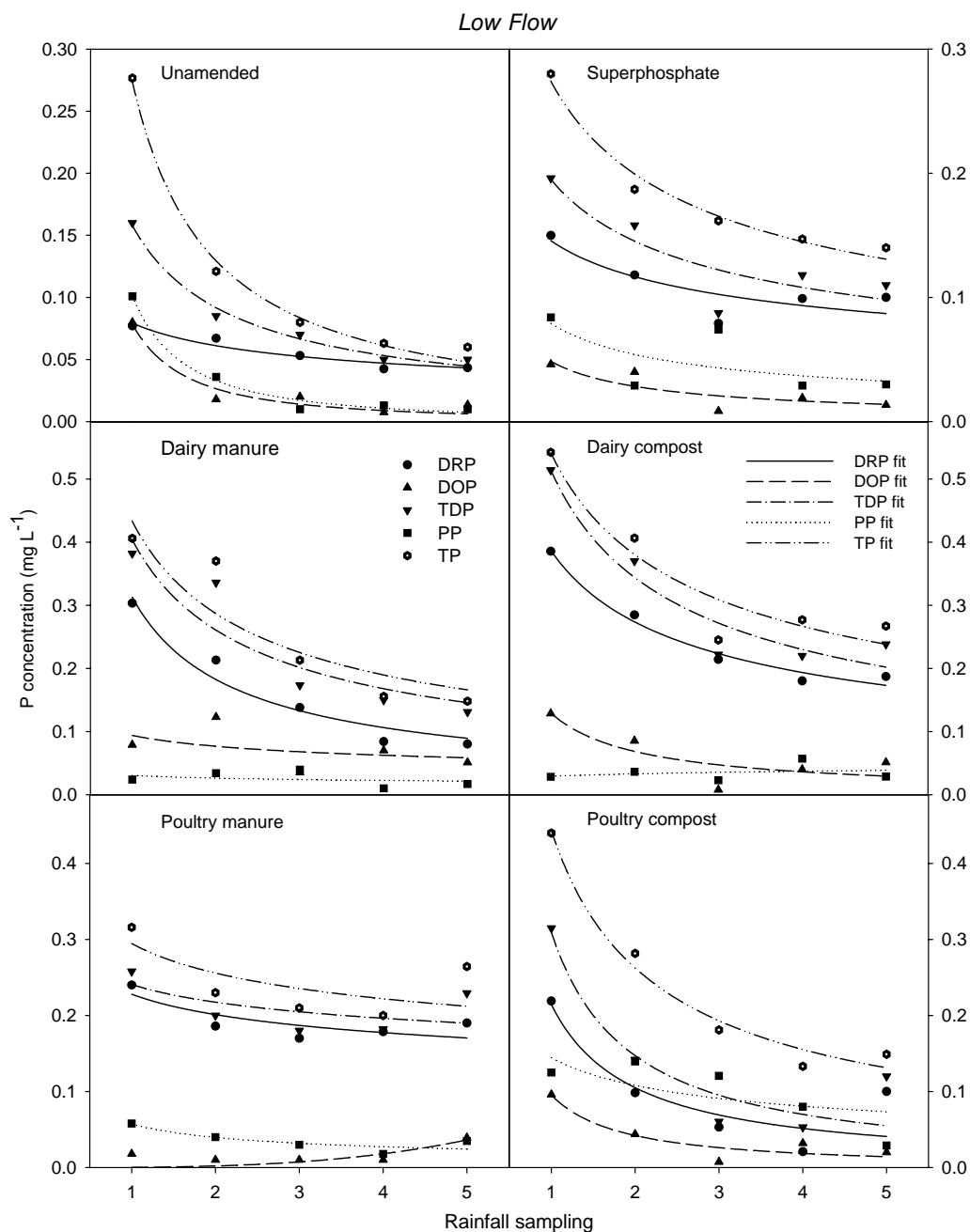


Fig. 3. Variation in the concentration of each P fraction and their corresponding fits to a power function ($y = \alpha t^\beta$) lost with each drainage sampling for the unamended dairy manure soil and soils amended at 200 kg P ha^{-1} low-flow rate lysimeters. Note the different concentration scales.

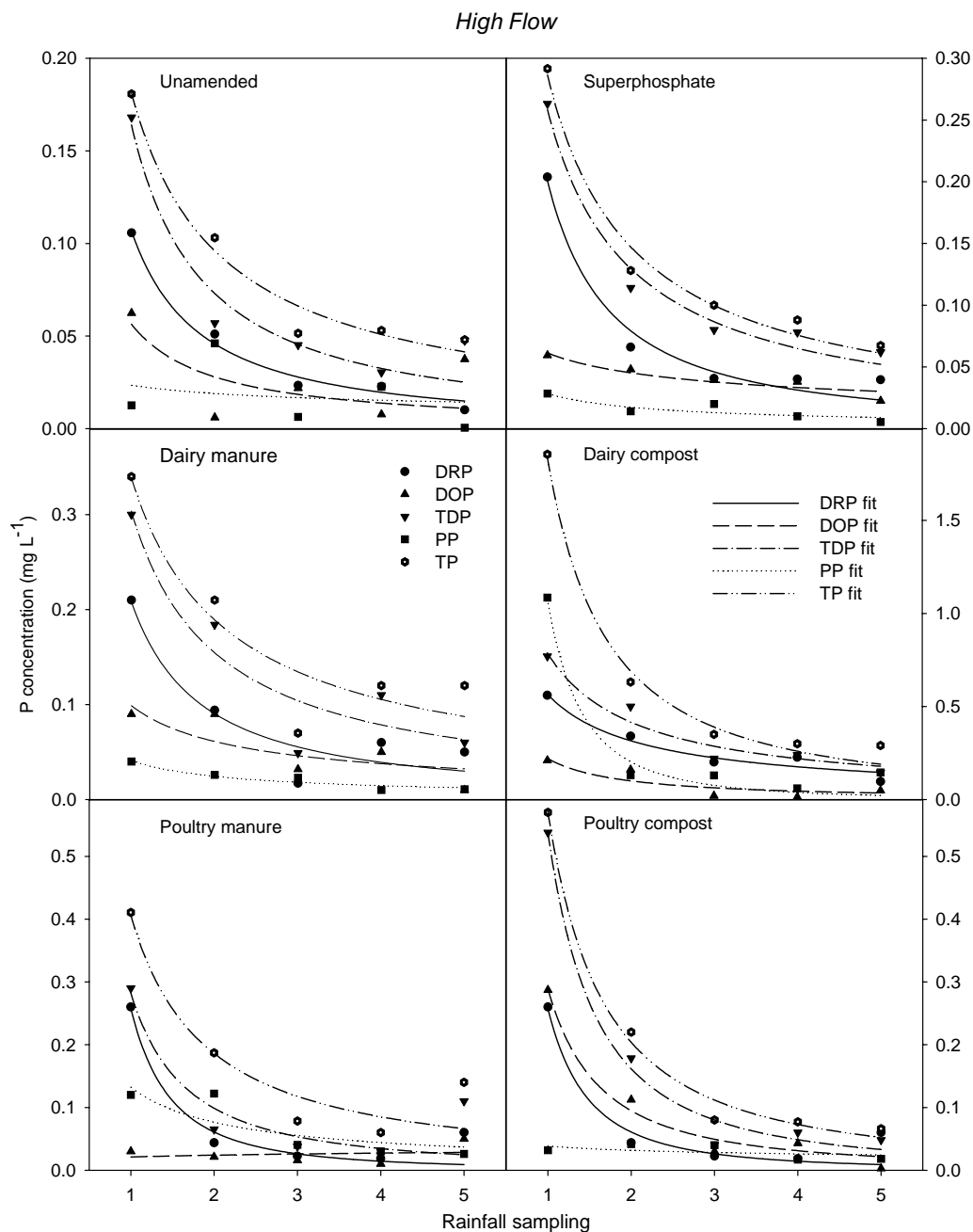


Fig. 4. Variation in the concentration of each P fraction and their corresponding fits to a power function ($y = \alpha t^\beta$) lost with each drainage sampling for the unamended dairy manure soil and soils amended at 200 kg P ha⁻¹ high-flow rate lysimeters. Note the different concentration scales.

Table 4

Correlation coefficients for the relationship between the rate of DRP exhaustion and Mehlich-3 extractable P (mg kg^{-1}) or TP (mg kg^{-1}) for each rainfall rate and soil amendment

Rainfall rate	Soil amendment	Correlation coefficients for DRP exhaustion rate (β) with	
		Mehlich-3 extractable soil P	TP
Low	Dairy manure	ns ^a	ns
	Dairy compost	−0.90*	−0.97***
	Poultry manure	−0.86*	ns
	Poultry compost	−0.77*	−0.93**
	Superphosphate	ns	ns
High	Dairy manure	−0.94*	−0.84*
	Dairy compost	ns	ns
	Poultry manure	−0.88*	−0.97***
	Poultry compost	ns	ns
	Superphosphate	ns	ns

^a Not significant.

* Significant at $P < 0.05$ level.

** Significant at $P < 0.01$ level.

*** Significant at $P < 0.001$ level.

and their influence on P sorption–desorption. For example, the dairy manured soils would have received more than four times the organic material than the poultry manured soils and infinitely more than the superphosphate amended soils (Table 3).

There is conflicting evidence in the literature as to the effects of manure and composts on P chemistry. For example, Sample et al. (1980) and Zhou et al. (1997) found P sorption may increase when organic matter is associated with Ca, Al and Fe. Whereas, Bhatti et al. (1998) found that removing organic matter from a forested spodic soil horizon by hydrogen peroxide (H_2O_2) oxidation increased P sorption. Clearly, the type and quality of applied organic matter has a significant influence on the P lost. Indeed, Singh and Jones (1976) found that organic residues containing less than 0.3% P increased P sorption, thereby decreasing the potential for P loss. Those residues with more than 0.3% P, decreased P sorption and increased the potential for P loss.

3.3. Prediction of P loss

Commonly accepted limits for the eutrophication of streams or other flowing waters not discharging di-

rectly into lakes or reservoirs are 0.01 mg P l^{-1} for DRP and 0.1 mg P l^{-1} for TP (Dodds et al., 1998; USEPA, 1994). Eq. (1) can be used to calculate the number of samplings (or in-turn, days) required for drainage waters to reach these limits. For each soil, the number of days required is plotted against the soil's Mehlich-3 extractable P concentration in Fig. 5. This shows a good relationship between the two parameters ($P < 0.001$), and that, as expected, soils under the higher flow rate are P exhausted far quicker and require less time to reach environmentally 'safe' concentrations in drainage waters than soils under the low-flow rate.

Little data exists with which to compare this work. McCollum (1991) found that it took 8–10 years for a soil initially of 50–60 mg Mehlich-1 extractable P kg^{-1} to halve, while a soil of twice the initial concentration took 14 years suggesting the increased loss or utilization of P at greater STP concentrations. Unfortunately, for actual P losses in drainage waters, we are not aware of any studies, with which to compare ours.

The data presented in Fig. 5 was used to estimate the time it would take for P concentrations in subsurface drainage from a soil of 100 mg kg^{-1} (equivalent to our soil's threshold for enhanced DRP loss) to decline to 0.01 mg l^{-1} . It would take about 3 years for DRP to decline to 0.01 mg l^{-1} under high flow and about 6 years under low flow conditions (Fig. 5). However, we must remind the reader that the conditions used in our study reflect a best-case scenario (very high and sustained rainfall). Indeed, the soils used in our study, of which there is only one type, come from a region that commonly receives an annual precipitation c of 1000 mm, of which less than 40% is lost via surface and subsurface flow (McDowell and Sharpley, 2001). Depending upon where the soil lies in the landscape, the proportion of total runoff as subsurface flow can vary from as little as 10% to as much as 90%. Thus, the time frame for depletion of subsurface drainage P can only be fully evaluated with an expensive long-term trial.

3.4. Variation of P leached with flow rate

In all cases, a greater load of P is leached from those soil lysimeters receiving twice the rainfall as the low-flow rate (Table 2). This is also reflected by

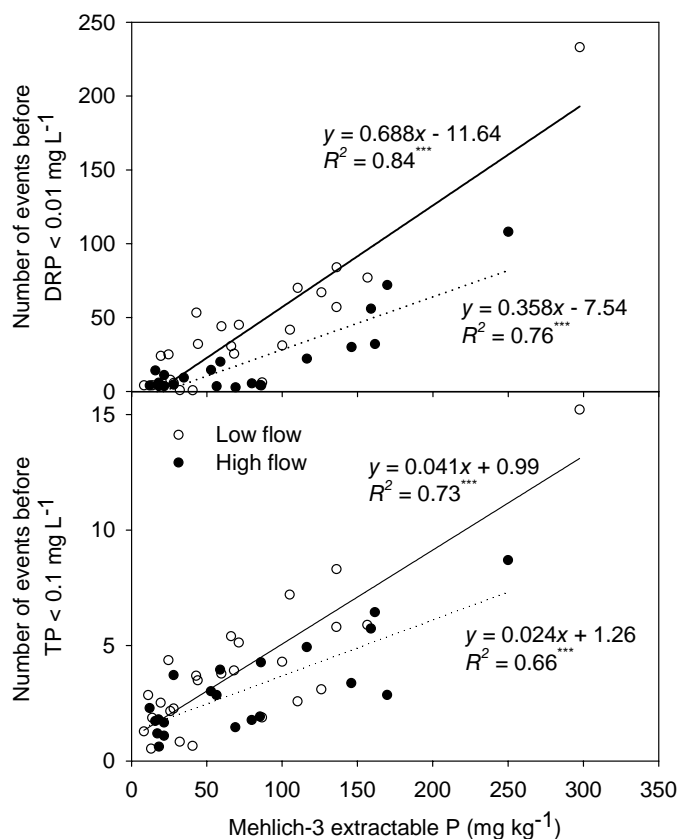


Fig. 5. Predicted kinetic depletion of DRP and TP for both flow rates to concentrations below acceptable levels. All linear regressions are significant at the $P < 0.001$ level (***).

the greater rate that P is leached by the high-flow rate lysimeters compared to the low-flow rate lysimeters. However, the overall loss from the high-flow rate lysimeters was not twice that from the low-flow rate lysimeters, presumably due to the faster exhaustion of P from the high-flow rate lysimeters.

In terms of P applied, TP leached from the low-flow rate lysimeters was 0.4, 0.7, 0.4, 0.3 and 0.4% of total amendment applied over 5 years (1875 kg P ha⁻¹; 5-year sum of 0, 25, 50, 100 and 200 kg P ha⁻¹) as dairy manure, dairy compost, poultry manure, poultry compost and superphosphate, respectively. For the high-flow rate lysimeters, this increased to 0.6, 1.4, 0.8, 0.6 and 0.4% of that applied for each respective amendment. Even so, it is unlikely that such conditions would occur in the field throughout the year, as much P loss in subsurface flow is mediated by quick-flowing

preferential pathways and not matrix flow (which may have accounted for the majority of flow conditions in this work). In contrast, it is also worth noting that evidence also exists to show that the supply of P loss to subsurface flow is controlled by the drainage of P from the soil matrix into preferential flow pathways (especially in the plough layer where well-defined macropores are ill-defined). As such, there is a need to estimate the size of this pool in order to identify those soils at risk and length of time P loss occurs at concentrations in excess of those that trigger eutrophication.

4. Conclusions

The data presented here indicated the effect of rain-fall intensity and duration and P management in the

longevity of accelerated P losses. Common among all soils was the dominance of dissolved P fractions (and especially DRP) in drainage waters and the increased loss of DRP and TP above Mehlich-3 extractable P concentrations of 100 and 130 mg kg⁻¹, respectively. As expected, the loss of P was far greater from high- than low-flow lysimeter soils and followed a pattern, which could be described by a power function. Among soils that received the same amendment, the rate of DRP loss (described by a rate constant β) was correlated to Mehlich-3 extractable P and TP. Further analysis of data, showed that the rate of P loss was related to, and could be estimated by, the initial Mehlich-3 extractable soil P concentration. This relationship can be used to approximate the average time required for this soil at a soil P threshold concentration of 100 mg Mehlich-3 extractable P kg⁻¹, to deplete in soil P reserves and yield an environmentally “safe” concentration in drainage waters (e.g., <0.01 mg DRP l⁻¹). However, while this relationship would probably hold true for most soils additional work would be required to establish the magnitude of the relationship as clearly soils with differing physiochemical properties would have different P exhaustion rates.

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